Transient Phenomena: Opportunities for New Discoveries

T. Joseph W. Lazio

Abstract Known classes of radio wavelength transients range from the nearby (stellar flares and radio pulsars) to the distant Universe (γ-ray burst afterglows). Hypothesized classes of radio transients include analogs of known objects, such as extrasolar planets emitting Jovian-like radio bursts and giant-pulse emitting pulsars in other galaxies, to the exotic, such as prompt emission from γ-ray bursts, evaporating black holes and transmitters from other civilizations. Time domain astronomy has been recognized internationally as a means of addressing key scientific questions in astronomy and physics, and pathfinders and Precursors to the Square Kilometre Array (SKA) are beginning to offer a combination of wider fields of view and more wavelength agility than has been possible in the past. These improvements will continue when the SKA itself becomes operational. I illustrate the range of transient phenomena and discuss how the detection and study of radio transients will improve immensely.

1 Introduction

The field of radio astronomy, and more broadly the recognition that multi-wavelength astronomy is important, resulted from a study of transient radio emissions. In the early part of the 20$^{\text{th}}$ Century, Bell Labs was interested in determining the source of transient radio interference on trans-atlantic radio communication links. This interest in transient radio interference resulted

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in a young engineer, Karl Jansky, building a radio receiver from which he was able to isolate various sources of interference. Two of these sources were indeed transients, related to radio emission from lightening, but the other source of "interference" was a steady source of celestial radio waves toward the center of the Milky Way Galaxy (Jansky, 1933).

While radio transients motivated Jansky's work, the celestial radio emission that he discovered was itself steady. Indeed, a New York Times headline announcing the discovery noted that its constancy was likely an indication that the emission was not the result of an extraterrestrial civilization. Subsequently, much of the work in radio astronomy assumed, either implicitly or explicitly, that the radio sky was largely unchanging. This assumption was consistent with the history of astronomy in which, with the exception of rare and dramatic events such as novae or supernovae, the sky was static.

A strong hint that the radio sky might be more dynamic than initially assumed was the discovery of radio pulsars (Hewish et al., 1968), which was awarded the Nobel Prize. With observations now covering essentially the entire electromagnetic spectrum, there has also been a growing recognition that the time domain represents a largely unexplored part of natural parameter space in astronomy. This recognition has been re-inforced by a series of observations over the past decade that have revealed a host of suprises regarding known classes of sources as well as potentially the discovery of new classes of sources. The recent European ASTRONET and U.S. Astronomy and Astrophysics Decadal Survey have emphasized the potential of time domain astronomy. The European ASTRONNET process produced a science vision for European astronomy (de Zeeuw & Molster, 2007), structured as a set of questions, for which time domain observations play a key role in answering. The U.S. Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics* (Blandford et al., 2010), explicitly named time-domain astronomy as a "science frontier discovery area."

The Key Science Program of the Square Kilometre Array has long encouraged a design philosophy for the telescope such that discovery of new sources and new phenomena is enabled (Carilli & Rawlings, 2004), and the dynamic radio sky may be one avenue for such discoveries (Cordes et al., 2004). More broadly, that the SKA will study transient radio emitters is in keeping with a trend in astronomy, across wavelength, for telescopes to search for transient sources, both electromagnetically (e.g., *Swift*, SkyMapper, LSST) and gravitationally (LIGO, VIRGO). Using examples and discoveries from the past decade, I illustrate how transients at radio wavelengths that might be studied with the SKA address some of the larger astronomical questions raised by both ASTRONET and *New Worlds, New Horizons in Astronomy and Astrophysics*. This selection is necessarily incomplete, but I hope that illustrates the breadth of possible topics that time-domain radio observations can address.

2 Lighthouse-like Brown Dwarfs

There is a strong correlation between the radio and X-ray luminosities of solar flares and stellar flares from main sequence stars, the so-called Güdel-Benz relation (Güdel & Benz, 1993). This relation holds across a range of stellar spectral classes, but it is becoming increasingly clear that very low mass stars and sub-stellar objects deviate, by potentially large factors (10^3 or more, Berger, 2006).

Dramatic indications of the extent to which brown dwarfs violate this relation have been intense radio flares observed from various objects, including pulsed radio emission from some brown dwarfs not unlike the emission from pulsars (Berger et al., 2001; Berger, 2002; Hallinan et al., 2007). This pulsed emission is consistent with an electron cyclotron maser operating in the magnetic polar regions of these objects (Hallinan et al., 2008). This emission process is the same one that produces the intense radio emission from the giant planets and Earth in the solar system, suggesting that extrasolar planets might also be detectable as transient radio sources (Lazio et al., 2009).

These observations indicate that there are significant changes in the structure of the coronae, magnetic fields, or both of stars as one considers stars of later and later spectral classes. In addition to being of interest in its own right, such astrophysical studies may also contribute to a better understanding of the Sun's corona and magnetic field ("What drives Solar variability on all scales?" Astronet). These play an important role in controlling the space environment around the Earth, upon which our technological civilization is increasingly dependent (e.g., satellite communications, navigation).

From the SKA perspective, many of the existing observations of the transient radio emission from very low mass stars and brown dwarfs has been at the "mid frequencies," typically between 5 and 10 GHz. An unexplored regime is at lower frequencies, below 1 GHz, and the analysis of recent observations of the planet HD 80606b suggest that observations below 100 MHz will be necessary to detect extrasolar planets (Lazio et al., 2010a). Much of the existing work has also targeted known brown dwarfs (or extrasolar planets, but see Lazio et al., 2010b), yet there may also be merit in all-sky surveys in an effort to find faint brown dwarfs that have escaped detection in previous infrared surveys.

3 Rotating Radio Transients (RRATs)

The ideal pulsar is a magnetized neutron star with a stable rotation that produces a completely regular pulse train. Soon after their discovery, however, it became clear that few, if any, pulsars obtained this ideal. Individual pulses vary in amplitude, both intrinsically as well as from propagation effects

(Rickett, 1970); some pulsars emit "giant pulses" (§4), and some pulsars exhibit "glitches" in which the pulsar rotation period actually changes (Börner & Cohen, 1971; Scargle & Pacini, 1971).

Taken to an extreme, one might ask if there are "pulsars" that emit only single, or very few, radio pulses. A re-analysis of a pulsar survey, in which the search was optimized for finding single pulses, did indeed find such pulses, from a class of objects now known as rotating radio transients (RRATs, McLaughlin et al., 2006). The identification of only a few objects, coupled with the realization that many more such objects had likely been overlooked in previous surveys, indicated that the Galactic population of neutron stars likely had been underestimated by a significant factor (2 or more), possibly resulting in tension with the estimated Galactic supernova rate (Keane & Kramer, 2008). Coupled with the increasing number of other classes of neutron stars (e.g., magnetars, accreting X-ray pulsars, compact central objects), the discovery of RRATs ties into larger questions of the possible end states of stellar collapse and the conditions during supernovae or in the progenitor stars that give rise to the diversity of neutron stars ("How do supernovae and gamma-ray bursts work?" Astronet; "What controls the masses, spins, and radii of compact stellar remnants?" NWNH)

From an SKA perspective, searches for pulsars, emitting either regular pulse trains or single pulses, are an important part of the SKA Key Science Program. These searches are likely to focus on frequencies around 1–2 GHz, in an effort to balance between lower frequencies (which optimizes for the typically steep spectra of pulsars) and higher frequencies (which mitigates interstellar propagation effects).

4 Probing the Intergalactic Medium

The majority of baryons in the current epoch are thought to be in large-scale ionized filaments that form "strands" of a "cosmic web" (Cen & Ostriker, 1999; Davé et al., 1999, 2001). Observations of highly ionized species of oxygen and neon by both the *FUSE* and *Chandra* observatories are considered to be validations of these predictions. Absorption observations along various lines of sight suggest a diffuse medium with a temperature of order 10^6 K with a density of order 5×10^{-5} cm^{-3} (e.g., Savage et al., 2005; Howk et al., 2009). While striking, these observations still suffer from the difficulty of probing only trace elements. The ionized hydrogen in the WHIM has not been detected directly.

The Crab pulsar emits so-called "giant" pulses—pulses with strengths 100 or even 1000 times the mean pulse intensity, at times out-shining the Crab Nebula itself (Hankins & Rickett, 1975). For many years, this phenomenon was thought to be uniquely characteristic of the Crab pulsar, but giant pulses have since been detected from the millisecond pulsars PSR B1937+21 and PSR B1821−24 (Cognard et al., 1996; Romani & Johnston, 2001) and PSR B0540−69, the Crab-like pulsar in the Large Magellanic Cloud (Johnston & Romani, 2003).

Cordes et al. (2003) and McLaughlin & Cordes (2003) assess how far away giant-pulse emitting pulsars could be detectable. They find that, even with existing instrumentation (e.g., Arecibo, GBT), giant-pulse emitting pulsars may be detectable over intergalactic distances (~ 1 Mpc). Because a plasma is a dispersive medium, any broadband radio pulses directly encode the electron (or plasma) column density in their frequency behavior. Consequently, detecting pulses from pulsars in other galaxies provides a direct measure of the intergalactic (ionized) hydrogen column density, and potentially of the local "cosmic web" ("Where are most of the metals throughout cosmic time?" Astronet).

From the SKA perspective, searches potentially can be conducted to much larger distances, encompassing more galaxies. Such searches will likely be conducted between about 0.4 and 1 GHz in order to balance the typically steep spectra of pulsars with the expected dispersion. Contrary to most pulsar searches, for which one objective is often to minimize the effects of dispersion, for studying the intergalactic medium, finding dispersion effects would be an advantage.

5 Electromagnetic Counterparts to Gravitational Wave Sources

There are a handful of double neutron star binary systems known. In at least two notable cases—PSR B1913+16, the "Hulse-Taylor" binary, and the more recently discovered "double pulsar" PSR J0737−3039—the orbits are decaying by an amount that is consistent with the emission of gravitational radiation from the systems (Burgay et al., 2003; Weisberg et al., 2010). Estimates are that these systems will merge within the next roughly 0.1–1 Gyr, depending upon the system, with the expectation that the merger will generate gravitational waves (Abadie et al., 2010). While no gravitational waves from merging neutron star systems have been detected yet, it is expected that these systems represent a significant source population for ground-based laser interferometric instruments.

There are expectations that a merger of a double neutron star system could produce not only a gravitational wave signal but an electromagnetic one as well. Hansen & Lyutikov (2001) make specific predictions based on certain assumptions about such a binary, but one might more generally expect that many gravitational wave sources could also produce electromagnetic wave signals (Bloom et al., 2009). Detecting objects both electromagnetically and gravitationally would increase dramatically the variety of information that could be extracted, such as greatly improved luminosity measurements (or limits) or detailed constraints on the physics of the gravitational wave event ("Can we observe strong gravity in action?" Astronet; "Discovery: Gravitational wave astronomy," NWNH).

From the SKA perspective, it is likely to be operational during a time when there will be both ground- and space-based gravitational wave observatories operating. Depending upon the success of Precursors and pathfinders, there are at least two operational models for the SKA to conduct coordinated gravitational-electromagnetic wave observations. In one mode, the SKA could follow-up gravitational wave alerts, either studying the sources themselves if their positions are well known or by conducting small "surveys" to search for transients or variable sources within the uncertainty region of the gravitational wave event. Alternately, the SKA could provide the source position, and other information, on potential gravitational wave events (e.g., particular classes of transients) that would enable gravitational wave detection to proceed with higher confidence.

6 Exotica

The sources described above belong generally either to populations of sources not originally throught to display transient behavior at all or are relatively straightforward extensions of known populations. There have also been discussions in the literature of what might be termed exotic objects. As examples, I highlight two classes of sources here.

Building on predictions of black hole evaporation (Hawking, 1974), Rees (1977) noted that the particles produced during the evaporation of a small black hole could interact with an ambient magnetic field (interstellar or intergalactic) and produce a radio pulse. Within some reasonable assumptions about the ambient magnetic field and the particle densities, such radio pulses could be detected from essentially anywhere in the Galaxy. Interestingly, the typical radio wavelength for the pulse scales as the magnetic field strength as $\lambda \sim 10\,\mathrm{cm}(B/5\,\mu\mathrm{G})^{-2/3}$. Given that the intergalactic magnetic field is lower than the interstellar field, searching at longer wavelengths would tend to favor finding black holes in intergalactic space. No such pulses have yet been found (O'Sullivan et al., 1978; Phinney & Taylor, 1979). One of the challenges of identifying such pulses could be that, by their nature, they would not be reproducible (Lorimer et al., 2007; Burke-Spolaor et al., 2010). Positive identification might rely on obtaining a large sample of pulses, from which other characteristics could be determined.

Soon after the widespread adoption of radio as a communication medium, it was recognized that it might be possible to use radio transmissions to communicate not only between countries but also between worlds (Cocconi & Morrison, 1959). Since that time, there have been numerous searches for radio transmissions (Tarter, 2001). While none have been successful to date, the radio band of the spectrum still represents a potentially fruitful exploration area: Among other considerations, only at radio and gamma-rays is the Milky Way Galaxy transparent. Because of limited sensitivity, previous searches for radio transmissions would have been able to detect only "beacons," signals intentionally aimed in our direction, and sufficiently distant beacons might be transient due to propagation effects (Cordes et al., 1997). However, with the sensitivity of the SKA, signals with strengths comparable to our strongest radars become detectable over interstellar distance, so-called "leakage" signals. Such signals might very well be transient because, for instance, the transmitter might be fixed to a rotating planet. As the beam of the transmitter swept through the sky, the SKA would be able to detect it only when illuminated (analogous to a pulsar). Detection of an extraterrestrial civilization would help address one of the most enduring questions of humanity.

7 Unknown Classes of Sources

The past decade has also seen the discovery of sources that have not yet been identified, of which there are two notable examples. The first example was GCRT J1745−3009, a transient discovered at 0.3 GHz in observations toward the Galactic center (Hyman et al., 2005). This source exhibited a series of outbursts, approximately 10 minutes in duration with a periodicity of 77 minutes. No counterpart was detected at other wavelengths, and speculations for the explanation of this source have included a brown dwarf or very low mass star, a so-called white dwarf pulsar, and a double neutron star binary (Hyman et al., 2005; Turolla et al., 2005; Zhang & Gil, 2005).

The second was a set of 10 transients discovered in nearly 1000 epochs over 22 yr of observations at 5 and 8.4 GHz (Bower et al., 2007). There is insufficient evidence to classify these transients, specifically no multi-wavelength counterparts, and they need not all belong to the same class of object. Possible explanations for these transients include orphan gamma-ray burst afterglows, isolated neutron stars, stellar sources, and extreme scattering events (Bower et al., 2007; Ofek et al., 2010).

8 SKA Science Pathfinding

The scientific promise of radio transients is being recognized among the SKA Precursors and Pathfinders. Transients are an explicitly recognized part of the key science case for many instruments (e.g., ASKAP, MeerKAT, LOFAR, MWA) or implicitly by being a significant fraction of the time awarded on the telescopes (e.g., EVLA). A recent example of the continued exploration of the

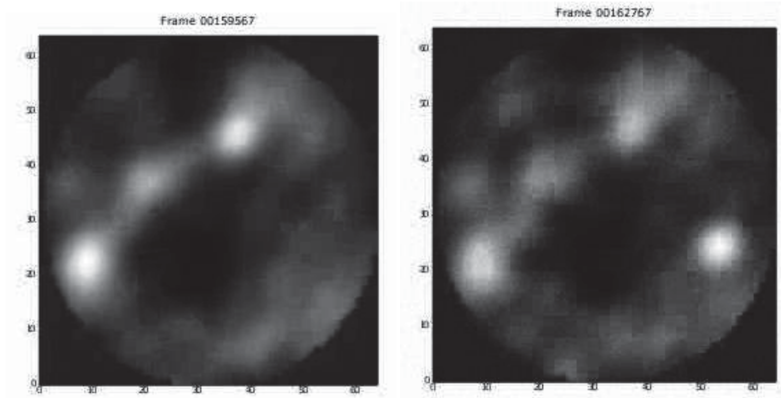

Fig. 1 Terrestrial radio transient captured by the Long Wavelength Demonstrator Array. (*Left*) All-sky LWDA image acquired at 60 MHz. The Galactic plane slopes diagonally from the upper right to the lower left and the sources Cyg A and Cas A are visible in addition to a general enhancement toward the inner Galaxy. (*Right*) An image acquired only seconds later. The dominant source is the reflection of a TV transmitter located hundreds of kilometers away, which is reflecting off an ionized meteor trail. While this particular transient would represent radio frequency interference (RFI), all-sky imaging at frequencies not used by TV or other transmitters could be a powerful way for aperture arrays to search for radio transients.

transient sky, with particular relevance to the low-frequency component of the SKA and its pathfinders was a short search campaign carried out at the Long Wavelength Demonstrator Array (LWDA). The LWDA was a 16-dipole, dual-polarization sparse aperture array, operating over the frequency range of 60 to 80 MHz, and located near the center of the National Radio Astronomy Observatory's Very Large Array (VLA). An all-sky imaging correlator was developed for it, and it took observations over the course of about 6 months. No celestial radio transients were detected (Lazio et al., 2010c), but Figure 1 illustrates the potential of an LWDA-like sparse aperture array for searching for transients.

In summary, the future for radio transients seems promising, both scientifically and technically. Scientifically, there are a host of questions, across the field of astronomy, that can be addressed by opening up the time domain at radio wavelengths. Technically, there are a host of instruments, either beginning to operate or that will soon be operating that will dramatically improve our knowledge of the radio transient sky, leading toward the construction of the SKA.

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